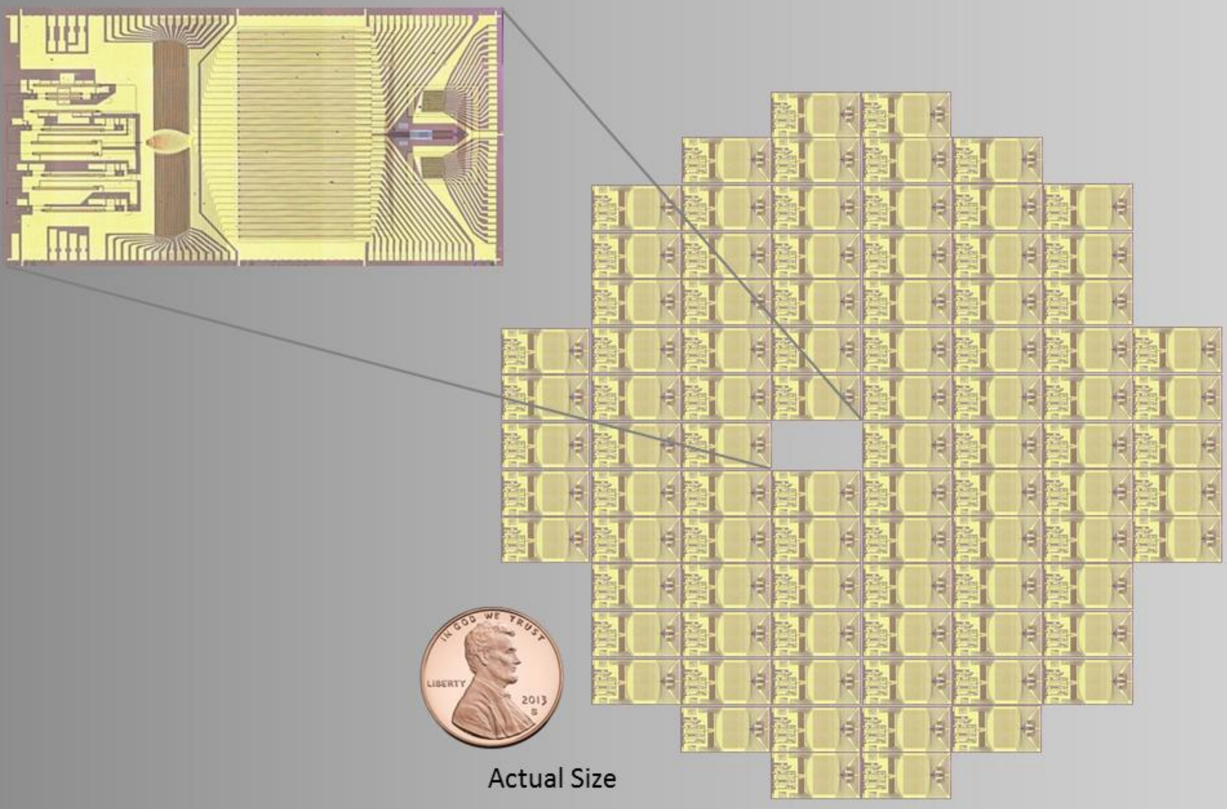
Department of Defense

RESEARCH & ENGINEERING

TECHNICAL ASSESSMENT: INTEGRATED PHOTONICS



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Executive Summary

Photonics is a branch of technology that broadly deals with the generation, modulation, transmission, and detection of photons as applied to fiber optical systems. Since the carrier frequency of the photons are typically very high (hundreds of terahertz), and the propagation loss in the optical fiber is very low (~0.2 decibels per kilometer), photonics technology has allowed for the transmission and processing of large amounts of analog or digital information at great distances, powering massive growth in data capacity of communication networks. This has enabled services like the internet, high performance computing, and power-efficient large-scale data centers. The DoD has already begun to capitalize on photonics technology in several areas, such as electronic warfare, chemical and biological detection, digital signal processing, quantum information science, and optics for free space applications. However major obstacles challenge the implementation of photonics to these areas. In particular, it is difficult to interface photonic systems with electronic systems, and even when accomplished, these systems have severe size, weight, and power restrictions. Integrated Photonic Circuits (IPCs) offer a way to circumvent these challenges by miniaturizing photonic systems and allowing for a broader set of applications for this technology. Broadly, an IPC is a compact highly integrated array of interworking photonic components such as lasers, modulators, photodetectors etc. arranged in specific functional configurations to provide power efficient, high-capacity interfaces to electronic systems.

The private sector has developed highly reliable IPCs for traditional digital communications applications in both long haul telecom and datacom networks. These are growth markets for IPCs and hence will continue to attract robust private sector investments for new product development. Thus the core IPC technology developed for the telecom sector now is available for the DoD to leverage and adapt to meet its application needs. Additionally, through public-private partnership, new efforts such as the Integrated Photonics Institute for Manufacturing Innovation (IP-IMI) have been launched to further develop a shared, mutually beneficial IPC ecosystem. However, the DoD has specific capability requirements that are unlikely to be fulfilled exclusively by private sector investments. To evolve IPCs beyond the realm of telecom into DoD specific areas requires targeted investment and research. The focus of this assessment is to determine the best way to posture DoD resources for the application areas where IPCs are expected to have an impact on DoD systems.

Defense Applications and Opportunities

Electronic Warfare (EW) Systems: DoD's future EW systems need to combat increasingly wideband signal threats and operate within smaller system size, weight, power, and cost (SWAP-C) constraints. Photonics is already finding applications within EW systems by enabling capabilities such as advanced aircraft self-protection, electronic intelligence (ELINT), and radar warning systems for land, air and space applications. IPCs are poised to enable SWAP-C efficient, higher performance, wider bandwidth processing systems on a chip. These systems on a chip will enable a wide variety of EW capabilities on smaller platforms with higher performance. The DoD's unique technical requirements dictate that DoD funding be focused on developing IPCs for EW as a technology program.

> *Recommendation:* Organize a working group dedicated to creating a technology development plan with near, mid- and long-term goals.
>
> *Recommendation:* Encourage program managers to pursue new development programs that utilize the capabilities of the IP-IMI and its major industry participants. This will leverage the existing >

$500 M investment effectively, and additionally any new DoD-specific IPC development that layers into the IP-IMI, and will help minimize duplication of existing efforts.

Chemical and Biological (CB) Detection: DoD needs compact CB detectors operating at a stand-off of several kilometers with laser sources that can vary over a wide range of wavelengths. IPCs have the potential to satisfy these requirements as well as reduce the size, weight, and power requirements for such systems, making them more relevant on the battlefield.

Recommendation: Develop a strategy across the services towards CB detection capability development with DTRA leading this effort. Such a strategy should leverage the existing telecom IPC toolbox of process technologies also known as process design kits (PDKs) for near-term system and sub-system demonstrations. In the medium-term, compact optical sources and photodetectors spanning near to mid-infrared wavelengths must be developed. The long-term strategy should provide visibility into the development of hybrid and/or monolithic integration technologies of a wide array of laser sources and photodetectors.

Recommendation: The DoD should organize its researchers working on CB-focused IPC technology and have this group meet with incumbent industry leaders in CB detection technology to encourage the development of IPC technology relevant to DoD CB requirements.

Quantum Information Science (QIS): The DoD needs advanced technologies such as quantum key distribution (QKD) for secure communications. This is one of many applications that can be enabled by the field of QIS. There have been a few promising demonstrations of such technologies by employing discrete photonic components. While QIS will benefit from IPC technology, our research indicates that IPCs have to evolve beyond the realm of telecom applications, and needs to significantly advance to reach the level of performance and complexity demanded by QIS applications. It is therefore our opinion, that as IPC applications evolve beyond telecom into other areas such as EW and CB over the next 5 years, the individual device performance, processing, integration complexity, and all associated design and fabrication tools would proportionately advance as well. As QIS applications evolve and mature during this same period, we envisage that IPC technology may be able to address QIS applications as the IPC technology toolkit would have the necessary resources at that time. We predict a timeframe of at least 5 to 10 years is needed for each area to evolve before a better assessment can be made.

Recommendation: The DoD focus on developing robust PDKs in other application areas and re-evaluate the possibility of IPC technology impacting QIS applications in 5 to 10 years as the performance and complexity reach levels demanded by future QIS applications.

Optics for Free Space Applications: The DoD is using optics in free space for a variety of applications including communications, infrared counter measures (IRCM), light detection and ranging (LiDAR). While IPCs have the potential to impact signal generation and processing in this diverse area, their biggest potential impact lies in optical beam steering subsystems. Here, IPCs have the potential to significantly reduce weight and cost while simultaneously improving operational reliability.

Recommendation: Coordinate efforts within the non-mechanical beamsteering applications. Issues encountered, and associated technologies should be common to most all applications.

Recommendation: Consider funding this area with a larger number of small investments as the technology is still in its infancy.

InP or silicon: Generally IPC technology is based on two material platforms: Indium Phosphide (InP) or silicon. In terms of technical capability, InP is more mature, having already achieved telecom-grade reliability, and currently is the industry market share leader in telecommunications applications. In contrast, silicon IPCs benefit from well-developed standards and fabrication techniques established by manufacturers of electronic integrated circuits. Commercially, silicon is being touted as a low-cost, low defect density material platform which can afford a high-degree of integration. However silicon-based IPCs are less mature and have not yet been able to secure significant market share away from InP-based IPCs. Given the respective strengths of both silicon and Indium Phosphide and the diversity of applications, both materials will continue to evolve as robust IPC substrate materials and carve out different niche applications.

Recommendation: Continue to invest in both InP and silicon IPC technology and let the technical requirements of applications dictate the material choice.

Production challenges: In IPC technology, as with silicon integrated circuits, the wide availability of PDKs would enable the design/fabrication ecosystem. However, developing such an elaborate ecosystem from the ground up is an expensive proposition and could cost a few billion dollars. Fortunately, the private sector has made a significant investments in both silicon and InP. However, the commercial sector is focused on fairly robust market opportunities predicated on bandwidth growth, which is projected to grow at a cumulative average growth rate (CAGR) of about 21 % in the 2013-2018 timeframe. The potential DoD market on the other hand is expected to be a very small fraction of the commercial telecom/datacom market, but the applications enabled are fairly significant and critical to national security. The major challenge in realizing IPCs for DoD lies in developing a cohesive strategy that maximizes the existing investments of industry leaders, who have already made significant investments in IPC technology. The IP-IMI is tasked with coordinating and leveraging this investment to expand the capabilities of IPC technology. However, DoD-specific IPC needs will require additional investment as this is beyond the scope of the IP-IMI base effort.

Recommendation: Invest in programs that intend to expand IPC platform capabilities that address DoD-specific needs within the existing framework of the IP-IMI to ensure maximum overlap with prior government and commercial investments.

Recommendation: Institute a policy that protects any DoD-specific technologies developed to restrict access to such technologies and their production facilities if necessary to non-US entities as appropriate.

Human Capital: The IP-IMI is taking the lead in implementing a workforce development plan to expand the core competencies in IPC technology as it relates to US education institutions. In addition, there presently exist several leading scientists within the DoD in both Integrated Photonics itself and in incorporating Integrated Photonics into DoD applications. However, there is a lack of highly experienced program managers in key positions to advocate or implement future strategies.

Recommendation: Sponsor general student fellowships in integrated photonics, both at the Service academies and at US universities, encouraging graduating students to accept postdoctoral opportunities which could also serve as a recruiting tool.

Recommendation: Develop or use existing programs that offer full salary support for employees of the Service labs to attend graduate school for durations of 2 to 4 years to better develop and educate the workforce in IPCs for DoD-specific applications.

Conclusion

This assessment presents a cohesive strategy, which aligns basic and applied research, develops human capital, and leverages existing commercial investment where possible to engage the integrated photonic circuits community to address several important DoD application needs. If this strategy is implemented, the DoD stands to benefit tremendously in the future.

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Introduction

As the demands of information processing increase, traditional electronics are beginning to reach their physical limitations for size, power, and speed. Integrated photonics offers a means to push beyond these limitations by processing information as photons, as opposed to electrons, allowing for greater data bandwidths and faster processing speeds. However, photonic designs are currently limited in their ability to interact with electronic systems, necessitating the development of integration technology. An integrated photonic circuit (IPC)[1] is a collection of many disparate photonic devices, such as lasers, modulators, and photodetectors integrated on a common substrate. Working together, these devices accept electrical signals, generate photons, and process such signals in the photonic domain before eventually converting photons back into electrons, allowing the IPC to interface with real-world electronic systems, such as computers.

The goal of this assessment is to identify opportunities that would improve the DoD's ability to leverage IPC technology. After a brief introduction and overview of IPC technology, we consider potential defense applications that we assess can benefit from IPC technology. Here, we consider the following 4 areas as potential DoD areas of interest: 1) electronic warfare (EW), 2) chemical and biological (CB) detection, 3) quantum information sciences (QIS), and 4) optics for free-space applications. We address how the DoD may harness the power of IPCs to realize relevant applications as well as common issues in adopting IPC technology and conclude with actionable recommendations.

IPCs: A Mature Technology with Emerging Applications

Background

We live in a highly networked age where connectivity is central to many facets of our personal and professional lives. Consequently, the information sharing services and resources we routinely demand are predicated on the delivery of high-bandwidth services. At the same time, new computing paradigms such as cloud computing have resulted in companies such as Google and Facebook developing and commissioning large-scale data centers, consisting of massive clusters of servers interconnected by network nodes such as routers and switches. They are housed in facilities that can occupy several 100,000s of sq. ft. and consume tens of megawatts of power which is enough to serve the needs of 50,000 single family homes. Illustrated in ***Figure 1*** [1] is the growth in global internet protocol traffic as a function of time by local access technology. Photonics continues to play a critical role in enabling this critical bandwidth distribution infrastructure. The low propagation loss of light waves in the optical fiber, and the wide spectral bandwidth available at optical frequencies has allowed for efficient high-capacity systems encompassing ultra-short reach (a few micrometers distances) through long-haul (thousands of kilometers) communications distances. These properties have led photonics technologies to find applications largely based in the telecom industry. Here, user demand for bandwidth has grown

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[1] The industry-wide terminology for Integrated Photonics Circuits (IPCs) is: Photonic Integrated Circuits (PICs). In this report, we will be using IPCs

consistently and is projected to grow at a cumulative annual growth rate (CAGR) of > 20%. Photonics has largely enabled this market that is now valued at over $6.5B.

While historically photonic communication systems have relied on arrays of interconnected discrete components (e.g. laser, modulator, receiver) mounted on large line cards, in the last several years the convergence of several factors have driven interest and investment in IPCs for communications. Two primary factors drive such investments: higher data capacity and port density, and reduced cost and power consumption. IPCs allow these systems to attain higher levels of performance and reliability, even above the 100+ Gbps speeds already achieved. Presently, the communications applications are using both indium phosphide (InP) and silicon IPCs to enhance speeds and lower power consumption. InP dominates in long distance applications, and both InP and silicon are finding applications in shorter distance applications such as data centers and high performance computing.

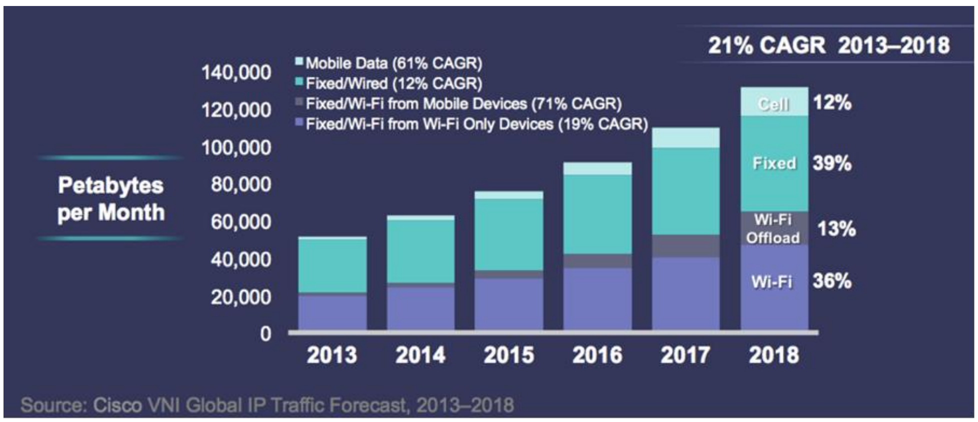

Figure 1: Growth in internet protocol traffic by local access technology

The commercial sector's interest in large scale communication applications of this technology largely aligns with DoD goals. The concerns of speed, power consumption, reliability, and cost cut across both civilian and military sectors. As a result, commercial investments that help to lower the cost of IPCs would be equally beneficial to the DoD. Additionally, technologically there is much commonality between the components needed for communications and those needed to meet emerging DoD needs, such as high-speed on-board communications systems for mobile platforms. Here, we note that DoD's higher technical requirements may necessitate targeted investments to achieve IPC technology enhancements. While IPC applications in DoD systems may be an emerging area, the core underlying IPC technology is actually reasonably mature and can readily be adapted to meet DoD future needs.

The performance, size, weight, power and cost (SWAP-C) benefits of the IPC has spurred investments across Europe, Asia, and North America, and has driven improvements in both IPC capabilities, with increasing chip and data density, as well as manufacturing techniques, since many of the techniques used for electronic integrated circuits are now being applied to IPCs. Illustrated in *Figure 2* is a timeline of the increase in integration density of IPCs. At the time of this writing, over 500 optical components have been successfully integrated in an InP IPC [2]. This IPC can enable a data capacity of approximately 0.5 terabits per second, which is roughly equivalent to the capacity needed by 10,000 broadband internet connections each operating at 50 Mb/s.

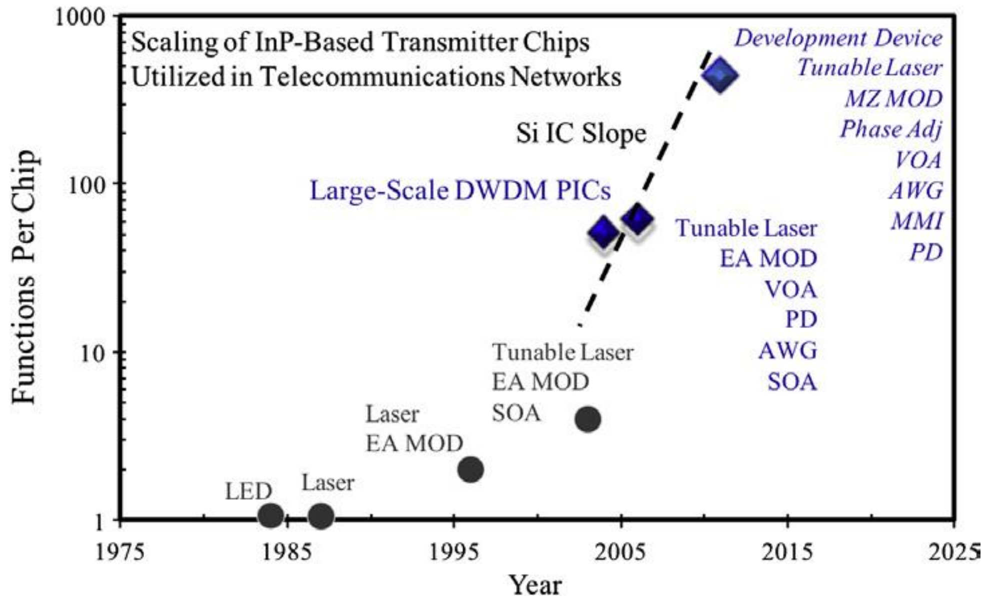

Figure 2 10 x 10 Gb/s IPC and timeline of increase in integration density

The impacts of these improvements can be seen in the interest of the private sector in IPC innovation. Since 2000, over $4B has been invested in IPC development by a multitude of companies, both domestically and abroad. This can also be highlighted by looking at the patent activity, delineated by both technology thrust area and by year. Figure 3 shows a strong increase in patent activity since 2000 when the search terms focus on integration. Before 2000, photonics technology was focused on discrete device development. The sudden increase in patent activity in 2000, combined with the sustained patent activity through 2013 showcase the commitment of the private sector to build a strong patent portfolio for integrated devices.

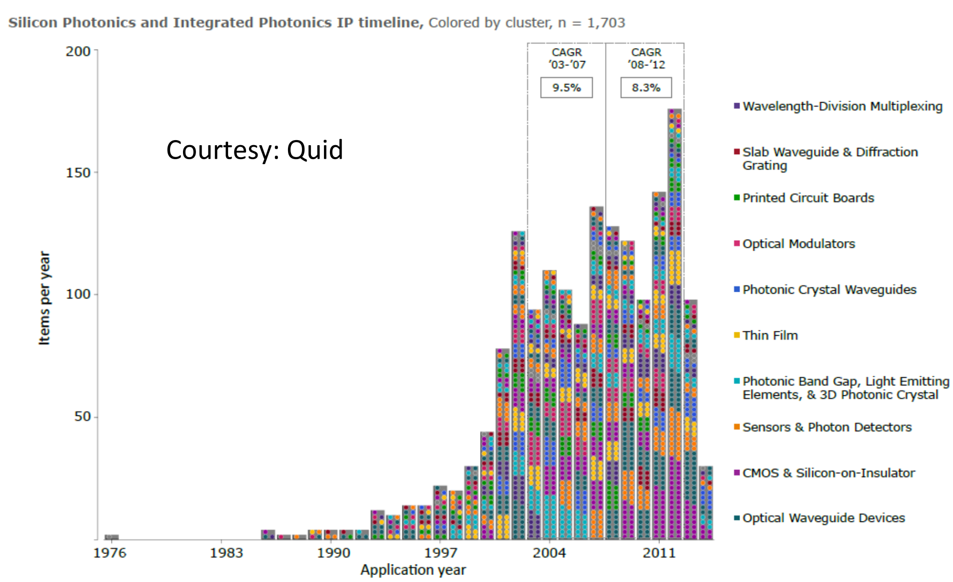

Figure 3 Timeline of patent activity in IPCs

IPC Technology Material Platforms: InP vs. Silicon

Generally IPC technology is based on two material platforms: InP and silicon. In terms of technical capability, InP is more mature, having already achieved telecom-grade reliability and currently is the industry market share leader in telecommunications applications. Furthermore, InP is more resistant to temperature variations, and can support active devices such as lasers, which are difficult to fabricate on silicon. However, across the industry, there are no standardized design rules for InP fabrication processes. Most of the commercial InP IPC technology in the US has been developed by the company Infinera, based in California. Infinera has made significant investments to develop this technology and mature it to the point of field deployment. Thus, they have well established proprietary design rules and process methodologies which are not shared with the rest of the community. Moreover, Infinera does not sell its IPCs as stand-alone products, but incorporates them into their optical data transmission systems. Currently the DoD is working with Infinera through the Integrated Photonics Institute for Manufacturing Innovation (IP-IMI) to open up access to this technology for DoD usage and other possible uses. Infinera is receptive to this idea with the caveat that these applications do not compete with Infinera's core communications applications. A portion of the IP-IMI's resources are dedicated to providing Infinera's capability to the larger DoD community through development of the design tools and software to allow outside users access to Infinera's process. Outside of the US, most of the effort into InP manufacturing is located in Europe, especially in Germany, the UK, and the Netherlands.

Unlike InP IPCs, silicon IPCs have only seen limited fielding primarily because of some of the challenges associated with incorporating optically-active elements. For instance, InP is known as a direct band-gap material, which is a necessary requirement for lasers or applications in optical enhancement. Silicon though, is not a direct band-gap material, and achieving similar applications with silicon IPCs requires complex hybrid integration techniques with more suitable direct band-gap materials. Aside from these complications, however, silicon IPCs benefit from well-developed standards and fabrication techniques established by manufacturers of electronic integrated circuits. Silicon IPCs also have the advantage of being able to directly integrate with silicon complementary metal-oxide semiconductor (CMOS) technology, commonly used in the electronics industry. Commercially, silicon is being touted as a low-cost, energy efficient and low defect density material platform which can afford a high-degree of integration. However, to date, technical performance has limited their application space to short haul communication applications. Because this market segment is projected to be high volume because of the potential uses in data centers and high performance computing, silicon IPC manufacturing has enjoyed investment from a host of players, particularly in Europe, which continues to drive its development. However, large scale commercial deployment has yet to occur, and InP devices still lead in overall market share.

The contrasting material properties and the differences in the state of technology maturity and availability between InP and silicon beg the question: which material platform is better suited for DoD applications? While often thought of in competing terms such as VHS vs. Betamax, these technologies have complimentary applications, each with their own, unique advantages. The situation is more analogous to previous comparisons between Gallium Arsenide (GaAs) and silicon for monolithic microwave integrated circuits (MMICs). Here, both platforms have evolved robustly, and have carved out niche applications. Low-power, high volume applications tend to be silicon based, and high-power

applications are typically GaAs based. Given the respective strengths of the different material platforms, and the diversity of applications, the DoD should strive to develop both material platforms as applications dictate. It is our opinion that with respect to IPCs both silicon and InP will continue to evolve as robust IPC substrate materials, and carve out different niche applications. Ultimately, it should be the technical requirements of each potential application that should dictate the particular choice of any material platform solution.

The IPC Ecosystem

For traditional electronics the ecosystem for circuit designs is highly evolved. With the notable exception of Intel, companies that focus exclusively on chip design are generally decoupled from companies that focus solely on device fabrication. This has enabled what is termed a fabless manufacturing model wherein the industry supports companies that do design and contract out fabrication to a semiconductor foundry.

IPC technology can follow a similar model, decoupling the tasks of design, fabrication & packaging, and design verification and layout. Europe has taken the lead in enabling a fabless IPC ecosystem. For example, the Joint European platform for InP-based Photonic Integrated Components and Circuits (JePPIX), in the Netherlands is a consortium facilitating an alliance to support fabless InP designs [3]. In the current nascent phase of IPC technology maturation, demand is typically low. A consortium of members allows for designs from different design groups to be consolidated onto a “multi-project wafer” (MPW), lowering development and prototyping costs for design validation. MPW runs allow small users who require only small portions of the wafer area to prove out designs for research purposes. Furthermore, the ability to aggregate designs from a group of small users to average down the development cost per user is a significant benefit of MPWs. Generally, MPW services are coordinated through a foundry “broker” who aggregates the designs, maintains proprietary boundaries, and prepares the full-wafer project for submission to a suitable foundry. The MPW concept has important implications during the R&D phase of any product when volumes are typically low. It also allows for the participation of small businesses and universities who otherwise may not be able to participate because of high entry costs. The consortium based organizational model can ensure that proper fire-walls are maintained between the different members, while verifying that the different designs conform to rules established by the foundry that fabricates the MPW. Thus MPWs serve to bridge the gap between the designer and the device fabricator, lowering the cost of entry for small companies and universities, thereby expanding the playing field. The IP-IMI is tasked with implementing an MPW program for silicon IPCs and InP IPCs, although the InP MPW service, being offered from Infinera, may have non-compete restrictions as noted previously.

The rest of the IPC ecosystem is supported by the development of design and layout tools. Such tools must perform the functions of: integrated photonic circuit simulations, physics based optical mode solving, process visualizations, verification, and design rule checking. Functionally, such tools are much similar to the suite of electronic design automation (EDA) tools that continue to facilitate silicon CMOS design. Again, Europe is a leader in this area for IPCs, along with companies in North America, such as Lumerical Solutions, Inc. [4], based in Canada. In certain applications, such as optical interconnects, these design tools need to work in concert with the electronic design tools. To facilitate this, companies

such as Phoenix Software are partnering with EDA leader Mentor Graphics [5] to collectively enable a joint photonic-electronic design paradigm.

Design tool suppliers typically work with foundry service providers to incorporate process design kits (PDKs) into their design tools. Broadly, PDKs contain all relevant design related information: design rules and mask layer information, a library of validated building blocks, simulation models and settings, and die and package templates. Each PDK is unique to a specific foundry and is based on design rules that conform to their unique processes. Since PDKs are validated from design through fabrication, they enable the designer to choose various photonic components from an available design library to create an IPC design. Designs can then be fabricated in a foundry supported by that PDK.

InP IPCs: JePPIX MPW Ecosystem

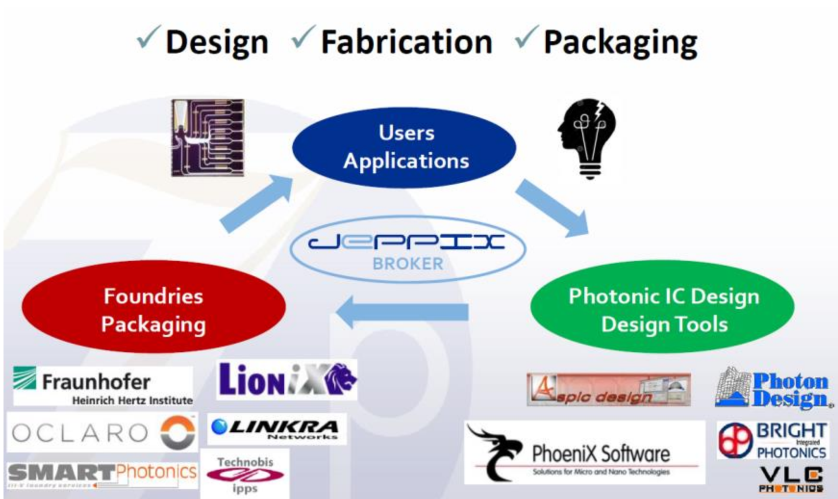

Figure 4 Current InP IPC ecosystem

The current JePPIX InP IPC ecosystem is pictorially depicted in *Figure 4*. The silicon ecosystem is very similar to this except that the players are different. As shown, the consortium plays a key role in brokering services among the designers/users, design tool suppliers, and foundries/packaging entities. We note that we are still in the nascent phase of the evolution of the IPC ecosystem, and there is significant fragmentation in markets, products, and associated players. It is therefore highly likely that the model for the IPC ecosystem will continue to evolve and change as applications and products reach higher levels of maturity.

Potential Defense Applications

While IPCs could conceivably be applied to any area requiring information processing, we have identified several areas of particular relevance to the DoD. These areas represent both gaps and opportunities for DoD as well as highlight the focus of private sector investment. Electronic Warfare Systems, Chemical and Biological Detection, Quantum Information Science, and Optics for Free Space Applications have been identified as DoD needs where IPCs can make a dramatic impact on future DoD system performance and even enable new operational capabilities. It is envisioned that commercial IPC

technology can and should be leveraged to address the needs of the DoD for these applications. However, it will be necessary to develop DoD-specific capabilities to augment commercial activities, providing an IPC capability that can satisfy the demanding DoD performance requirements.

Electronic Warfare

Some of the most demanding antenna systems are associated with Electronic Warfare (EW), which is a military action aimed at controlling the use of the electromagnetic (EM) spectrum for combat capability. EW is generally divided into 3 areas: Electronic Support (ES), Electronic Attack (EA), and Electronic Protect (EP). ES is action to search for, intercept, identify and locate intentional or unintentional EM transmitters for the purpose of immediate threat recognition. EA is the use of the EM spectrum to attack with the intent of degrading, neutralizing or destroying the enemy's use of the EM spectrum. EP is action taken to protect our electronic systems from any effect of friendly or enemy employment of EW that degrade, neutralize, or destroy friendly use of the EM spectrum. The "winner" of the electronic war is the combatant able to best utilize and control the use of the EM spectrum *at the lowest overall burden*, in terms of SWAP-C.

Changes in the battlefield environment have greatly affected the calculus of this burden. The heightened challenge for EW stems from electronic devices for radio signals becoming very inexpensive, readily available, and easy to use. As a result, the warfighter is faced with highly advanced EM signals, high power jamming signals, and a proliferation of threats in a cluttered EM environment. The new warfighter environment demands dramatic change to our systems in order to sense weaker signals in the presence of strong ones, sense more signals from more locations, transmit more information and more power, continuously sense/process, reject unwanted signals, and to make EW widely available. EW systems are particularly challenging because, even though the adversary's signal bandwidth may be narrow, their frequency range is generally unknown and so our EW systems must cover an asymmetrically broad spectrum.

Of particular note is the proliferation of weapon systems utilizing frequencies greater than 20 GHz, which exacerbates the strain on EW systems designed to detect, engage, and counter these threats. Current DoD capabilities in the millimeter wave spectrum (30-300 GHz) severely lag the capabilities in the legacy microwave regimes (below 20 GHz). EW system designers often respond with parallel systems to handle numerous frequency channels. However, this leads to a multiplication, by 100 or more, of the SWAP-C—a substantial disadvantage as compared to the threat system. The DoD is in need of new technologies to manage the asymmetric EM threat and to maintain lethality and survivability.

Integrated photonics technology can address these issues in several ways. Most prominent, optical frequencies are about 40,000 times greater than electronic frequencies: compared to the bandwidth of a radar signal (~100 MHz), the capacity of an optical fiber (~ 4 THz or 4,000,000 MHz) is significantly larger. This enormous bandwidth is what has fueled the telecommunications revolution over the past four decades. Through integration, complex photonic functions could be densely packed with control electronics, reducing power consumption, and yielding a significant jump in EW system performance, especially in the millimeter wave (20 to 110 GHz or higher) frequency regime. This could give the US a

tactical electronic warfare advantage and allow the assured use of the EM spectrum while simultaneously denying it to our adversaries.

Photonics may also improve US capabilities in this domain by allowing for greater signal purity, lower signal loss, lower weight, and immunity to electromagnetic interference. This could produce operational advantages through improved timing, managing contested/cluttered EM environments, and enhanced signal interception and recognition. Moreover, with the same energy loss, signals carried by an optical wave in fiber will travel over 2,000 times farther than radio signals in conventional copper cable. Finally, these capabilities can be developed in systems with dramatically lower SWAP-C burdens. For example, a current RF filter requires a volume of 6000 mm^3 (about the volume of a ball point pen), an equivalent optical version would only take up 0.1 mm^3 (the equivalent of about an inch long human hair). As many EW systems require potentially hundreds of these components, photonics may enable both more efficient fielding of EW devices as well as improving their capabilities.

As EW system requirements necessarily dictate low-noise and high linearity, InP based IPC technology is likely to provide a better solution to EW system needs as compared to silicon. This is based on the performance of devices reported in peer reviewed literature for both InP and silicon. In view of this, it is expected that this technology advantage of InP for EW applications will continue for the foreseeable future.

Chemical and Biological Detection

Chemical and biological (CB) agents pose a continuing threat to the United States and our allies. This can come from the efforts of adversaries, such as the discovery of chemical weapons in Syria, as well as natural threats such as the 2014 Ebola outbreak in Africa. In the field, warfighters are laden with a substantial amount of equipment, and CB detection equipment is often seen as simply an additional burden. Currently, the smallest chemical agent detector is the Joint Chemical Agent Detector (JCAD) weighing approximately two pounds with a space 40 cubic inches. The “low tech” alternative to this is the M8/M9 paper which is smaller and lighter, but has only limited applications to certain types of agents. Meanwhile, biological detection is difficult because of the fact individual sensors are only tuned to individual threats, and comprehensive detection requires a large sensor battery, often over 40 lbs., too large to be worn.

In addition to the size and weight limitations of these detectors, their capabilities are also limited. The advent of non-traditional agents wherein there is a time lag between exposure and detection challenges the utility of conventional CB detectors. Additionally, CB detectors also suffer from limited range. While DoD has been able to develop short-range capabilities, it has struggled to field effective three to five kilometer stand-off detectors for CB agents, whose early warning would provide warfighters with critical time to assume appropriate protective postures.

IPCs have the potential to drive CB detection equipment forward by adding additional capability to detect new toxic materials with improved sensitivity and selectivity while also reducing SWAP-C. Reducing SWAP allows units to deploy more sensors across multiple platform types, increasing the overall effectiveness of the detection system. They may also improve performance as many of the

optical techniques used for detection of these substances, such as hyperspectral imaging, spectroscopy, and Raman scattering require short range infrared lasers operating over a wide wavelength range (200 to >> 1500 nm). These approaches would benefit greatly from the parallelism afforded by integrating multiple wavelength lasers onto a single IPC package, yielding better species selectivity and faster system response. Finally, using optical detection through telescopes, warfighters may be able to achieve stand-off range CB detection, further enhancing force protection.

CB detection is an area receiving little commercial investment, but is of great importance to DoD. Current systems suffer from a number of drawbacks, limiting their utility to warfighters. Considering these issues DoD investment in enabling these areas through IPCs could have substantial impact in improving their deployability and effectiveness, saving the lives of warfighters from weapons of mass destruction, and would allow the US to sustain combat operations in hostile environments.

Quantum Information Science

In Quantum Information Science (QIS) information is treated as physical and is processed according to quantum mechanics rather than classical mechanics. Since this extends the physical implementation to the ultimate limits of currently understood physics, QIS involves the limits of physically allowable information processing. This has been shown to possibly include dramatic increases in information processing capacity for certain problems. This is relevant for general information processing, but it is especially important for security and encryption. For example, the robustness of encryption systems is presently based on the ability of classical electronic computers to solve problems such as factoring large semi-primes[2]. Based on the level of encryption, it can easily be calculated on how much time is required to break the encryption key with a classical electronic computer. If that time is deemed too short for securing the data, a longer encryption bit sequence can be used. However, if quantum computing can evolve to a useful scale, code-breaking algorithms will become exceedingly efficient and new forms of encryption will be needed in order to secure information. Thus, QIS is a topic of great interest to the DoD because it enables a wide range of applications spanning more efficient computers for code breaking to more secure information transmission than what is possible with today's classical technologies.

Quantum information processing is performed on quantum bits or "qubits." One readily accessible implementation of qubits is as single photons of light. So processing light at the single photon level is an approach to implementing quantum information processing. The complexity of quantum information applications grows with the number of photons involved in the processing and the degree to which those photons are entangled,[3] but this also requires increasing amounts of optical hardware.

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[2] Semi-primes are numbers that are products of precisely two prime numbers. The public key in RSA encryption involves a semi-prime, which when factored provides information to decrypt the cipher-text. RSA encryption is secure because this factoring problem is computationally difficult.

[3] Entanglement refers to the quantum mechanical property of two or more physical objects sharing a quantum state. There is no classical analog to this, though one can think of it as the individual objects having no well-defined individual independent states while *correlations* between measurements of the states of the individual objects *do exit*. The mathematical predictions have been verified beyond doubt over the 100 years since the inception of quantum mechanics.

Quantum key distribution (QKD) is the simplest application of QIS, as it can be achieved with single photons or pairs of entangled photons. QKD has been implemented in discrete photonic components precisely because it involves only single or paired photons and is fairly immune to noise, so the complexity of the circuits is acceptable. Current secure communications occur by distributing encryption keys in advance. A physical hardware key is used on both ends of a link and a secure channel is established. However compromise of a physical key can occur and can jeopardize our secure communication infrastructure. QKD is a means to distribute keys electronically and securely when needed, thus potentially eliminating the need to assure the safety and integrity of physical hardware keys.

A more complex application of QIS can be found in quantum sensing, which generally requires an order of ten photons, and those photons are in particularly simple states. While noise issues become relevant here, they do not impact the measurement process and may not need further suppression. Quantum sensing exploits entanglement to achieve high sensitivity signal detection such as could be used for rotational sensors used for navigation (gyroscope) applications.

The most complex type of processing is quantum computation. Quantum computing is unlikely to show benefits over standard computing techniques until one hundred to one thousand qubits can be manipulated at once. However, present demonstrations have shown the capability to couple a few to tens of qubits together. In addition to the large number of qubits, quantum computing requires that the atomic states be completely general. Beyond those basic requirements, any quantum information processing photonic device must exhibit very high dimensional stability, meaning that even minute changes in their optical path lengths can greatly disrupt their interactions. As a result, the elements of any photonic quantum computation system must be stabilized and controlled to a very small fraction of a wavelength.

Photonic QIS is currently limited by several obstacles. The first is the availability of deterministic sources of photons in well-defined quantum states. This requires the photon source to be integrated into the device performing the computation, which requires sophisticated development of micro-systems and integration into hybrid constructs. Advances in IPC technology through integration of quantum dots into more complex optical circuits would be a major advance in photonic quantum computing.

The second limitation to be overcome is the complexity that can be achieved while maintaining very high degrees of optical path length stability. This is currently impossible with macroscopic construction and the consensus in the research community is that the only solution to these challenges will come from developing advanced IPCs constructed on a single slab of substrate crystal. In contrast to discrete optical elements bolted to an optical table, IPCs are of nanometer scale precision. This makes them intrinsically precise enough to manipulate photons to the needed fraction of a wavelength.

The final requirement is the detection of photons with high efficiency. Current detection techniques operate at impractically short wavelengths or have very low efficiency at useful wavelengths. Making efficient use of such detectors would require hybrid circuits, and currently beyond the state of industrial manufacturing for IPCs.

The impacts of developing the capabilities of QIS would be relevant over the near and long term. In the immediate term, the use of QKD to enhance cryptography indicates the range of applications that will

become important. Every application using cryptography can be "upgraded" to use QKD. This could greatly impact overall information security across DoD. Quantum sensing is the application domain next closest on the development horizon. The applications of interest here include detection of adversaries' assets, Positioning, Navigation, and Timing (PNT) applications, and high sensitivity signal monitoring of different environments. Here, sensor applications based on high precision interferometry will become increasingly valuable. Measurement of environmental parameters, stress, strain, vibration, etc. will become useful tools to monitor the activities of adversaries. Taking advantage of photonic quantum information processing in sensing applications will require increasingly complex and most of all stable and precise optical circuits. This likely cannot be achieved other than through the techniques of IPCs.

In the long term, quantum computing is a technology that makes some classes of problems that are currently impossible into the realm of solvability. Here, the "killer app" is the development of decryption technologies against current generations of cryptographic methods. This could provide DoD with a host of new capabilities, but would also pose a serious threat to a large portion of US communications security (COMSEC). Since QIS based sensors and systems are still in the research phase, it is difficult to predict which IPC material platforms will best suit the needs of this applications area.

Optics for Free Space Applications

Free space optical (FSO) communications has been a term associated with the transfer of digital data between two locations forming a point-to-point communication system where the propagation medium is free space as opposed to optical fiber. FSO systems have the distinct advantage of providing a high bandwidth data channel between two locations without requiring any prior physical connections between locations, as the setup only requires that terminals be placed at both distal ends of the link. FSO communications have the additional advantages in that it provides an extremely high bandwidth, is a relatively covert channel that is not subject to RF frequency allocation limitations, is difficult to detect, and nearly immune to jamming techniques due to its high degree of directionality. Disadvantages often associated with FSO communications are: limited periods of availability due to weather (poor visibility), and since FSO is naturally a point-to-point link, the locations of the ends of the link must be known beforehand.

FSO communication links have been investigated for many applications across DoD. Recently, the Marine Corps has begun investigating FSO for terrestrial links between towers and for ship-to-shore communications to augment traditional RF communication links. The Navy is considering using visible FSO communication links for underwater short-reach communications to allow for communications that do not require tethering or a hull-penetrating physical link. Other applications include Air-to-Air, Air-to-Ground and Ground-to-Air links. Links with satellites have been demonstrated through the GeoLITE program (Lincoln Labs), as well as similar programs originating in Japan and Germany. NASA has recently demonstrated a high-data-rate link from earth to a satellite in Lunar orbit and is considering FSO for data links to Mars.

Another important optical free space application is Infrared Counter Measures (IRCM). For IRCM, light from lasers is used to disrupt or distract an infrared guided missile from hitting its intended target. Countermeasures are accomplished by using a pointer/tracking system aboard a platform to direct a laser towards an incoming missile that is using an infrared tracker designed to detect the blackbody

emission from the platform. The laser can be used to saturate the detection system or to confuse it through various modulation patterns to cause the missile to lose track and thus miss its intended target. Typically, countermeasure systems use mechanical means to physically direct beams. These systems generally have significant SWAP penalties, however, which limit their use.

FSO systems can also be used for detection such as in Light Detection and Ranging (LiDAR), which encompasses an entire class of distinct systems that use light as the carrier to essentially perform a function similar to what radar might be used for in the RF domain. In LiDAR, encoded light is projected out to illuminate the surroundings and the return signal is processed to yield a “picture” of the environment. LiDAR systems are presently used to perform a number of applications including satellite laser ranging, self-driving autonomous vehicle guidance, imaging for target identification and robotics, remote sensing, avionics applications for sensing wind speed and turbulence, as well as some classified applications. As an example, the Army has deployed the Long Range Biological Standoff Detection System (LR-BSDS) which is a helicopter mounted system using LiDAR intended to detect man-made aerosol clouds out to 30 km or more.

IPCs have the potential to impact optics for free space applications in a number of key areas. For FSO communications and LiDAR, IPCs could improve the signal processing circuits that are used to generate the transmit data streams/waveforms. IPCs will also be useful to implement adaptive receiver circuits that offer better capabilities against turbulence and beam breakup due to the properties of propagating optical beams in a turbulent medium like the atmosphere or sea water. Traditional FSO links operating in turbulent media have usually relied upon adaptive optical systems or receiver diversity techniques to mitigate turbulence. The requirements for FSO communications in these areas would suggest that InP based IPCs would be more relevant than silicon due to the technology similarities with long haul fiber-based communication systems.

For IPCs used within the FSO applications as part of the signal processing functions, the operational impact will include more capable systems with lower SWAP-C. The arguments are similar and follow that of the other applications discussed above. Additionally, there has been significant interest to switch to non-mechanical optical beamsteering for reduced SWAP and improved reliability in FSO systems. If non-mechanical beamsteering can be achieved with the total power and field of view needed in a robust and reliable package, a significant advancement in DoD capabilities will be realized. Mechanical pointer/tracker systems with bulk optics often represent 90% of the system weight and are responsible for the majority of failure mechanisms. Non-mechanical beamsteering using silicon IPC technology could prove to be an enabling capability to deploy FSO systems on a wider variety of platforms while simultaneously improving reliability and reducing maintenance costs. A few demonstrations have been performed in silicon including efforts by DARPA’s Short-range Wide-field-of-view Extremely agile Electronically steered Photonic EmitteR (SWEEPER).

Harnessing the potential of IPCs to realize DoD applications

DoD-Specific Technology Investments

IPCs based on InP or Silicon

Generally IPC technology is based on 2 material platforms: Indium Phosphide (InP) and silicon. There is a certain amount of scientific “hype” surrounding silicon, however, in terms of technical capability, InP is more mature, having already achieved telecom-grade reliability, and currently is the industry market share leader in telecommunications applications. In contrast, silicon IPCs benefit from well-developed standards and fabrication techniques established by manufacturers of electronic integrated circuits. Commercially, silicon is being touted as a low-cost, low defect density material platform which can afford a high-degree of integration. However silicon-based IPCs are less mature and have not yet been able to secure significant market share away from InP-based IPCs. Presently both material platforms have the potential to impact DoD applications. InP appears to be more important for Electronic Warfare applications, whereas both InP and silicon appear to be relevant for CB detection, QIS, and optics for free space applications. QIS and Optics for Free Space applications most likely require both technology platforms. Given the respective strengths of both silicon and InP, and the diversity of applications, both materials will continue to evolve as robust IPC substrate materials and carve out different niche applications.

> **Recommendation 1: Continue to fund both InP and silicon IPC technology and let the technical requirements of applications dictate the material choice.**

Electronic Warfare

The DoD has the responsibility to control the use of the electromagnetic spectrum. For IPCs to affect a broad spectrum of EW systems, the performance of the underlying devices within the various foundry PDKs used to fabricate IPCs will need to improve dramatically, especially in terms of the excess noise contribution of an IPC system-on-a-chip. Current PDKs supporting commercial applications do not offer the low-noise performance demanded by EW systems. If IPCs had the necessary performance and were as accessible and mature as electronic integrated circuits through improved, standardized, and widely available design, manufacturing, testing, packaging, and assembly tools, then they will provide the capability to design dramatically smaller EW systems covering wider instantaneous bandwidths with both improved and new capabilities. The development of DoD-specific components, PDK enhancements, materials and manufacturing techniques would impact a broad spectrum of EW systems and subsystems. While other efforts have suggested that a significant investment (~200 M$) is needed for IPC technology to have a large impact to many systems, a smaller and more targeted investment could be effective to realize individual new system capabilities. A number of smaller investments (5-15 M$/Year) could then be used to build capabilities over time in much the same way that millimeter wave monolith integrated circuits (MIMIC) and silicon electronics capabilities have evolved.

> **Recommendation 2: Establish a program to develop IPC technology for EW applications similar in management structure to the MIMIC program, addressing the broad interests across DoD as well as other government entities such as DTRA and DOE. The effort should also be coordinated with the efforts of the DoD-led Integrated Photonic Institute for Manufacturing**

Innovation (IP-IMI) so that the DoD can layer any DoD-specific IPC PDK enhancements on top of the existing plans to best utilize the resources the DoD is already investing in IPCs and MPW shuttle runs via its 22 M$/year investment (plus 100 M$/year private cost share) in IP-IMI.

Recommendation 3: Develop a strategy across the services to implement a short-, medium- and long-term technology development effort to create DoD IPC capabilities for EW. This should be organized across the services for cost efficiency via a subgroup that reports to ASD(R&E) through the EW Community of Interest. It is anticipated that all three services will be involved in this process as well at technical experts from DARPA and FFRDCs as appropriate.

Recommendation 4: Leverage the substantial commercial work by engaging the foundries participating though the IP-IMI and encourag new programs to work within this industrial technology base. Working with the leaders in the commercial marketplace will maximize the DoD investment dollar. By working with participants in the IP-IMI, the DoD will effectively leverage improvements made by this consortium and any PDK enhancements that are dual-use. If the DoD were to pursue IPC technology in a separate new program, the cost barrier to entry for IPCs would be higher so working alongside the commercial enterprise is recommended.

Recommendation 5: Focus service funding on plan development and execution. Technical experts suggest that 0.3 to 0.5 M$/Year is needed to organize and develop a plan with additional investments steered to develop specific platform capabilities. If coordinated with the capabilities of the IP-IMI, this additional investment can be carefully planned and executed to minimize overall cost. Participation by government technologists would be necessary, especially in the early years of the program to help define and set priorities for technology development through demonstration programs that highlight the importance and capabilities of the technology.

Recommendation 6: Coordinate PDK enhancements across the DoD application areas. This requires the services to include in their development plan a strategy using multiple foundry platforms and hybrid integration to address the DoD-specific needs available in the near term from each platform. By including several foundry platforms, more technical progress can be made in the near-term. This also leverages the DoD investment across multiple disciplines to yield potential cost savings.

Chemical and Biological Detection

The rapid expansion of biotechnology is fostering a great deal of commercial development within the medical community. The healthcare industry provides a large commercial market for products developed by industry, with substantial carry-over potential into the DoD biological detection area. However, there is little commercial demand for CB stand-off or point chemical agent detection, highlighting a potential area for DoD investment. Such CB detectors needs laser sources that can vary over a wide range of wavelengths to detect an array of CB agents. The current generation of IPCs for telecom tend to focus on specific wavelengths. This represents a significant gap in IPC capabilities, which DoD may be able to address by developing compact optical sources and photodetectors that span a

wide variety of wavelengths from the near to mid-infrared range of the optical spectrum, as well as multi-spectral optical sources.

> **Recommendation 7: Develop a strategy across services towards CB detection capability development with DTRA leading this effort. Such a strategy should leverage existing IPC PDKs for near-term system and sub-system demonstrations and therefore this effort should participate in any larger IPC development strategy effort. In the medium-term, compact optical sources and photodetectors spanning near to mid-infrared wavelengths must be developed. The long-term strategy should provide visibility into the development of hybrid and/or monolithic integration technologies of a wide array of laser sources and photodetectors.**

> **Recommendation 8: Incentivize incumbent industry leaders in CB detection technology to adopt and develop IPC technology relevant to DoD requirements. This is paramount to ensuring that the technology is not only developed, but is successfully transitioned into a system or sub-system.**

Quantum Information Science

The DoD has a unique need to ensure the absolute security of sensitive communications. Quantum Information Science offers the potential to disrupt what we currently understand to be secure. IPC technology may have potential to realize quantum information applications due to the mechanical stability of the substrate. IPC technology must also include the structures to implement quantum information processing. IPCs incorporating quantum dots, non-linear optical elements, and high efficiency detectors generating electrical signals, all integrated into a single device in a mass production environment are beyond the current state of the art. So, building advanced IPCs for quantum information processing will require extensive research and development in IPC technology.

From an applications perspective, QIS is still an evolving field and is still in its nascent phase. Our research indicates that the technology of IPCs need to evolve way beyond the realm of telecom applications, and needs to significantly advance to reach the level of performance and complexity demanded by some QIS applications. It is therefore our opinion that as IPC applications evolve beyond telecom into other areas such as EW and CB, the individual device performance, processing, integration complexity, and all associated design and fabrication tools would proportionately advance as well. We project that at that time the IPC technology toolkit would have the necessary resources to address some of the QIS applications. We envisage a 5 to 10 year timeframe for such advances to be made.

> **Recommendation 9: Until further resources develop, continue to fund conventional QIS research and advance the field so that such advances can be leveraged when IPC PDKs evolve to a level of maturity demanded by QIS application needs.**

Optics for Free Space Applications

The DoD is using optics in free space applications for a variety of applications including communications, IRCM, LiDAR, as well as a few others. While there is some synergistic commercial overlap, the DoD has unique requirements in this area. The potential for IPCs to impact the signal generation/processing subsystems is good; however the biggest potential impact lies with the potential for IPCs to impact the

optical beam steering subsystems. Mechanical beamsteering systems are bulky, heavy and unreliable. IPCs have the potential to significantly reduce SWAP-C while simultaneously improving operational reliability. While optics for free space applications represents a very diverse topic, it should be possible to coordinate development efforts in future programs as the issues and technologies should overlap significantly.

> **Recommendation 10: Consider funding non-mechanical beamsteering IPC development with a larger number of small investments as the technology is still in its infancy and many ideas should be nurtured until a clear winner emerges. This could be accomplished with a tiered type of Grand Challenge program where seed-level funding could be awarded to large group of performers with a down selection to the most promising solutions for a continued larger investment. For other Free Space applications needing IPCs, new programs should be organized within the framework of the IP-IMI to benefit from maximum leverage and overlap.**

IPC issues common to all DoD applications

Based on our work, we have identified some issues that require action that are common to all IPCs, independent of their intended DoD application area. Such topics are covered here.

Production Challenges

A concern that should be of great interest to the DoD is the question of who are the commercial entities developing IPCs, where they are located, and whether they can be trusted. A recent report of the Defense Production Committee Act (DPAC) found that the U.S. telecommunications industry was by and large no longer able to produce the advanced equipment needed for the military, with most manufacturing now moved offshore. We concur with the recommendation that investment in new technologies, such as IPCs, be performed onshore with procedures designed to ensure production integrity [6]. The US has already proceeded down this path with the policies surrounding the IP-IMI execution. The IP-IMI is tasked with developing a domestic IPC manufacturing capability which presently includes domestic InP (Infinera) and silicon (SUNY) foundries. Furthermore, state of the art IPC development in silicon and InP does not require the smallest node dimensions (14 nm) as state of the art CMOS does. Therefore, these domestic InP and silicon foundry options are capable of producing state of the art IPCs onshore.

> **Recommendation 11: Continue to implement policies designed to ensure production integrity of IPC technology. This would include policies to limit accesses at US design and production facilities as well as procedures to validate systems/subsystems.**

High cost barrier to entry

In IPC technology, as with silicon integrated circuits, the wide availability of PDKs would enable the design/fabrication ecosystem. However, developing such an elaborate ecosystem from ground up is an expensive proposition and could cost a few billion dollars. Fortunately, the private sector has made a significant investment in both silicon and InP. Infinera has expended significant financial resources (see Appendix A) to develop a design and fabrication capability for fabricating IPCs for application in long haul telecom data transport systems. While this resource is not shared among the wider IPC community, and all IPCs manufactured by Infinera are consumed internally, it should be noted that Infinera has

successfully built and continues to operate a US based InP design through manufacturing ecosystem with telecom grade reliability and is in discussions with members of the DoD and DoD contractors to open their foundry for DoD use through the IP-IMI. Similarly, silicon photonics tends to also be company proprietary in the US; however in Europe, many universities and a few large and small companies are working to develop the ecosystem for specific short-reach datacomm applications such as cloud computing, virtual cables and high speed data centers. The IP-IMI is planning on organizing and developing the SUNY foundry into a manufacturing platform for wider DoD use.

The DoD should embrace the opportunity to leverage the large investment made by the private sector. Since DoD applications require the strengths of several material platforms, a cohesive strategy that reads across different material platforms/PDKs is needed to bring these important DoD's IPC applications to fruition. The IP-IMI has started the process of developing the technology along these lines.

> **Recommendation 12: Engage industry leaders in this technology to incentivize them to pursue applications of interest to the DoD through additional investments made through the IP-IMI. We should initially select applications that leverage and build upon existing commercial PDKs and align new DoD-specific technology developments where possible to the platform development spirals of the commercial industry to maximize the overlap and encourage participation.**

Small DoD volume

The commercial sector is focused on fairly robust market opportunities such as long-haul telecom and datacenters (see 0) where product demand and volumes are predicated on bandwidth growth, which is projected to grow at a CAGR of ~ 21 % in the 2013-2018 timeframe. The potential DoD market on the other hand is expected to be a small fraction of the commercial telecom/datacom market, but the applications enabled are fairly significant and critical to national security. A challenge in realizing IPCs for DoD lies in developing a DoD investment strategy that maximizes overlap with commercial IPC activities where practical. To parlay commercial investments of the existing technology base into IPCs for DoD use is a win-win for both parties. An associated challenge is in determining which of the many DoD applications is appropriate to pursue initially, keeping potential DoD volumes in mind so that the DoD can develop the technology it needs.

> **Recommendation 13: Foster a plan to combine technologies from many material platforms into a single multi-chip module. This allows participation from a number of smaller enterprises who can respond to DoD-specific needs to integrate modules with those of industry leaders, thus creating a best of breed multi-chip module. This will allow for better near term technology demonstrations while allowing for longer term native improvements in each material platform's PDK.**

> **Recommendation 14: Prioritize those applications where IPCs offer benefits to DoD-specific applications and which have the fewest DoD-specific PDK enhancements needed to achieve the functionality required. This leverages the commercial PDK enhancements and keeps the DoD program focus aligned to the largest extent possible with the private sector. Where DoD-**

specific enhancements are needed across multiple PDKs, the investments should be prioritized based on a risk/reward trade off.

Programmatic issues

IPC is more of a component or subsystem-level capability that can impact many systems. It is similar to MIMIC in that respect. MIMIC was developed to address affordable phased arrays as a first application, but it evolved into supporting a huge number of electronic warfare and other applications, both DoD and commercial. The DoD invested over $2B into MIMIC over 20 years. In contrast, investments into IPCs for DoD applications are small, decentralized and primarily being pursued by systems programs. This is partially due to an inappropriate conceptualization of IPC development. Rather than approaching IPC technology as a system program having technology needs, it should be addressed as a fundamental technology that can impact a wide variety of systems.

Recommendation 15: Form a multi-agency government team to organize and architect a plan to develop IPC technology over the short, medium and long term.

Recommendation 16: Allow this team to develop a program to develop IPC by using a few high-impact DoD applications to showcase the technology and demonstrate the potential impact of further IPC developments.

State of Human Capital

The IP-IMI is taking the lead in implementing a workforce development plan to expand the core competencies in IPC technology as it relates to US education institutions. In addition, there presently exists several leading scientists within the DoD in both Integrated Photonics itself and in incorporating Integrated Photonics into DoD applications. However, there is a lack of highly experienced program managers in key positions to advocate or implement a well-constructed and well-coordinated investment strategy to move the technology forward.

Recommendation 17: Sponsor general student fellowships at both at the Service academies and at US universities to encourage the further development of human capital,

Recommendation 18: Target additional funding towards encouraging graduating students to accept postdoctoral opportunities with the Defense Department.

Recommendation 19: Develop a program that offer full salary support for employees of the Service labs to attend graduate school for durations of 2 to 4 years to better develop and educate the workforce in IPCs for DoD-specific applications.

Conclusion

A significant percentage of the commercial interest in IPCs is for communication systems and networks. Beyond these applications, IPCs have the potential to dramatically affect many diverse DoD applications by enabling smaller and more complex systems on a chip, particularly the areas of electronic warfare, CB detection, quantum information science, and optics for free space applications. While some of the technologies developed for communications systems can be leveraged in electronic warfare in the near to medium term, subject to appropriate enhancements to the PDKs to achieve better performance, CB

detection, quantum information science, and optics for free space applications will require significant enhancements to the technology suite.

The diverse requirements of these areas will continue to drive investments in both InP and silicon platforms, and DoD should invest accordingly. Likewise, the DoD must coordinate its IPC technology related programs across agencies. This will pave the way for the consolidation of programs with a view toward establishing a shared DoD ecosystem for different application areas. The DoD funded IP-IMI is taking the lead in organizing the industry. Any additional programs should be coordinated and layer their development on this industry consortium. If successful, these efforts will enable a robust foundation to support future U.S. military needs.

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Appendix A: Integrated Photonics Commercial Industry

Infinera

Infinera (NASDAQ: INFN) [7] is a leader and true pioneer in the design, development, and productization of InP IPCs. Founded originally in 2000 as Zepton Networks, Infinera received a pre-IPO investment of more than $350M. Early investors included marquee venture capital firms such as Kleiner Perkins Caufield & Byers (KPCB) [8]. Infinera has managed to leverage this investment to create their own vertically integrated ecosystem for IPCs that ranges from IPC design through fabrication, culminating in assembly and final testing. Their first product was a 10 channel x 10 Gb/s/channel IPC, with an aggregate data capacity of 100 Gb/s. Each such transmit IPC was comprised of an array of 10 lasers, 10 modulators, 10 optical amplifiers, a multiplexer, and a host of other power-monitoring and related photonic components on a single chip. What was previously done with over 100 discrete photonic components, Infinera managed to integrate into a single chip. It is particularly noteworthy that Infinera was able to assemble this complex IPC and qualify the technology for telecom grade performance and reliability. In so doing, Infinera also achieved excellent wafer fabrication yields. As shown in *Figure 5* [2] Infinera's InP IPC yields rival silicon CMOS yields.

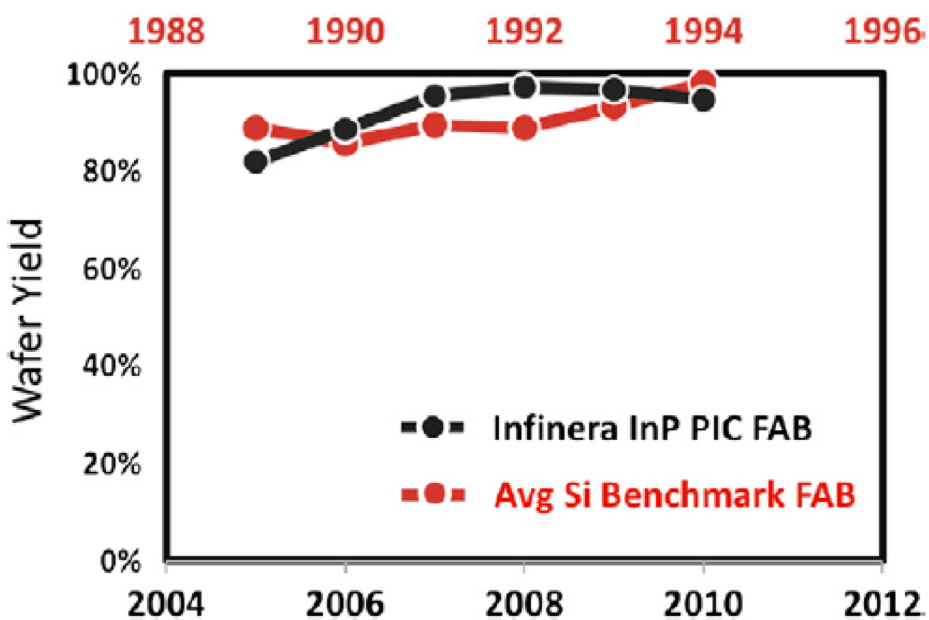

Figure 5 Wafer fabrication yield (normalized to 10 mask levels) for a state-of-the-art InP IPC fab (Infinera) and average Si CMOS (1989-1994)

However, the end IPC product is not sold in the open market but is used in Infinera's telecom data transport system products. Thus, the complete suite of tools, design through fabrication and final testing

are proprietary to Infinera. Notwithstanding that, Infinera does possess the critical know-how for creating the IP ecosystem from the perspectives of both technology and process.

With the demand for data in all segments of the network growing at an insatiable pace, the high level of photonic component integration that Infinera's IPC platform gives them a huge leg up in the marketplace. Infinera's current generation IPCs have an aggregate data capacity of 500 Tb/s [2] and employs complex coherent modulation and demodulation schemes. To date, with nearly 300 patents to its credit [9], Infinera has an enviable patent position in the InP IPC space. Infinera's CY14 revenues were ~ $ 670 M, primarily from the sale of data transmission systems, and the net operating income was ~ $ 14 M. The part of the revenue attributable to IPCs is not separately called out. At the time of this writing, Infinera's market capitalization was ~ $ 2.5 B.

Appendix B: Commercial Sectors Relevant to IPC Technology

Long haul telecom

We live in a highly networked age where connectivity is central to many facets of our personal and professional lives. Consequently, the services and resources we routinely demand are predicated on the delivery of high-bandwidth services. The advent of video sharing services such as YouTube and Netflix as well as social networking services such as Facebook and Twitter have created significant demand for high-bandwidth services. Such demand coupled with new computing paradigms such as cloud computing has also resulted in the development and commissioning of large-scale data centers. Collectively such services have created an unprecedented demand for bandwidth. The bandwidth demand is quite robust, and capacity to meet a significant portion of this demand will have to be provisioned in the long haul telecom networks. Well-known US companies that maintain and operate long haul telecom networks include Verizon and AT&T. In addition, a host of web-scale and cloud operators are also deploying long haul networks. Web-scale operators include both content providers such as Netflix, and Amazon, and neutral providers such as Digital Realty, Equinix, and Rackspace. Cloud operators refers to companies such as Facebook, Google, and Microsoft. To accommodate future demand, the different network nodes (such as routers, switches etc.) have to grow both in port density and bandwidth provisioned per port. The best way to address this challenge is through a high degree of integration. In this regard, Infinera and their InP platform is a good case in point. They have been very successful in translating the value proposition of photonic integration into a very profitable business. The high capacity demands of long haul networks mandates a high level of performance with attendant reliability. Infinera has already parlayed the power of photonic integration into achieving commercial success in long haul networks. It is therefore fair to conclude that long haul telecom will continue to be a robust market for IPCs, and products for such markets will continue to be pursued by various commercial entities.

Data Centers and Data Communications

In a hardware sense, large data centers represent a collection of massive clusters of servers interconnected by network nodes such as routers and switches. They are housed in facilities occupying several 100,000s of sq. ft. in area, and consume several tens of MWs of power. Illustrated in *Figure 6* are various snapshots of a large data center used by cloud operators such as Facebook or Google. Optics in datacenters has grown at a > 10% cumulative average growth rate (CAGR) driven by growth in number of server ports and higher server speeds. This trend will only accelerate as web-scale and cloud operators deploy even higher speed (25 Gb/s & 40 Gb/s) servers. At such data rates even short reach (< 500 m) interconnections can benefit from photonic technologies. A further impetus to deploying photonics in datacenters stems from web-scale operators who tend to build datacenters with longer links (~ 2 km), and higher speed servers. In such situations, photonic technologies used in traditional long-haul telecom networks become quite relevant even to datacenter optics. However, considering the volume of optical products that future datacenters will demand, and the low average selling price (ASP) required to meet datacenter economics, future server port densities and speed can only be achieved

through a high degree of integration of photonics technologies. Thus IPCs are projected to have a key impact in datacenters.

Figure 6 Today's datacenters are massive in scale and data capacity

Appendix C: Integrated Photonic-Institute for Manufacturing Innovation (IP-IMI)

Background

There is substantial investment into integrated photonic circuits by the commercial sector, both in the US and abroad, highlighted by the Obama Administration's announcment for the formation of the Integrated Photonics Institute for Manufacturing Innovation (IP-IMI). The IP-IMI was awarded to the Research Foundation for the State University of New York in July 2015 and includes Tier 1 companies such as Infinera, Intel, IBM, GE and Hewlett Packard. The total investment includes 110 M$ Federal and 400 M$ (combined state & private). The IP-IMI is expected to create an end-to-end innovation 'ecosystem' in the U.S. for integrated photonics; including responsive domestic integrated photonics chip fabrication, foundry access, seamlessly integrated and standardized design tools, automated packaging, assembly and test, and workforce development. In addition, the IP-IMI will offer a MPW service to allow for lower cost R&D and prototyping activities. The IP-IMI will be structured to allow government, industry and academia to come together with the goal of organizing the currently fragmented U.S. capabilities in integrated photonics technology and better position the U.S. relative to global competition. The IP-IMI will also enable universities and small-to-medium enterprises to participate in and benefit from the Institute's manufacturing advances, with a focus on maturing technologies from Manufacturing Readiness Level 4 to 7.

The focus of the IP-IMI will be to organize and develop the entire ecosystem, including the capabilities that exist within the foundry PDKs. In this regard, the IP-IMI's focus on the PDK capabilities will be organized through a technology development roadmap that will be jointly outlined by the private sector and members of the DoD. Shown in *Figure 7* is a notional Venn diagram of PDK capabilities needed by both the commercial sector and the DoD. The IP-IMI will be focused on those PDK capabilities that have dual use and those needed by primarily commercial applications, although a lesser amount of DoD specific enhancements will be developed as well. Also shown in the diagram are those DoD PDK enhancements that would be the focus of any additional DoD efforts that can be layered on top of the IP-IMI ecosystem.

The risk to industry to develop and implement IPC technologies on their own is high, and access to this technology is limited due to increasing complexity, difficulty, and cost of entry. Competition on many fronts makes it difficult for individual small and medium sized companies to capitalize or develop these technologies for a global marketplace. The goal of the IP-IMI is to establish a national institute as a resource to focus on these complex issues in integrated photonics manufacturing, develop solutions to create cost-effective manufacturing capabilities that offset the risk to the U.S. industrial base in adopting these new technologies, all while using a collaborative approach between industry, academia, government, and the workforce. The ability to reduce the time and cost to bring products to the marketplace is a common need shared by both Government and industry. The goal of the institute is to

be self-sufficient within 5 years without further direct Government investment which implies a strong commercial bias. Commercial applications of IPCs however will primarily evolve component capabilities within their process design kits (PDKs) that satisfy commercial applications specifications. These PDKs may fall short of the more demanding specifications needed for devices that can impact a majority of DoD applications of the technology. It is incumbent on the DoD to fill this gap with a technology development plan that supports critical DoD system performance needs. This development should be layered with the goals of the IP-IMI to leverage to the extent possible the commercial application focus of the institute.

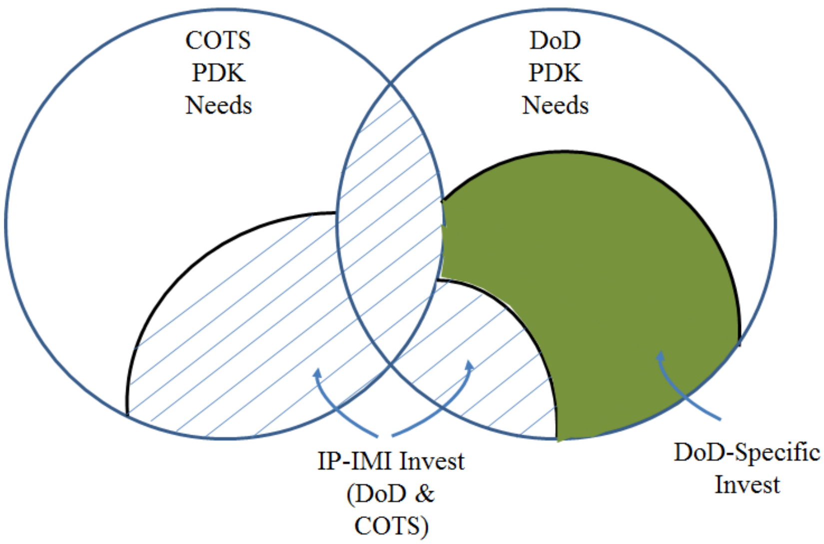

Figure 7 Venn diagram of COTS vs DoD PDKs

Appendix D: Non-DoD Government activities in IPCs

Similar to electronic circuits that have permeated all parts of life, IPCs will eventually be critical to numerous aspects of productivity, commerce, health, safety, and health. Initially, though, there appears to be heightened interest in four Departments: the Departments of Energy, Commerce, Health and Human Services, and Homeland Security. For three of these Departments, we examine the potential impact of IPC's on capabilities, potential for dual use, and the Departments' role with respect to resources and leadership. There is significant similarity in the technology needs of Homeland Security and Defense.

Department of Commerce

Within the Department of Commerce, IPCs can be envisaged to provide leap-ahead benefits in export control, treaty compliance, economic security, manufacturing, resource management, telecommunications, and national standards. Of these areas, the National Institute of Standards and Technology (NIST) is in the forefront of IPC development and adoption.

NIST acknowledges that integrated photonics is becoming important to a diverse array of NIST activities. One particular thrust is that of "NIST-on-a-Chip." Here, NIST seeks to move calibration and traceability from Boulder, CO to the user. Currently, precision measurements are performed in a sophisticated NIST laboratory. With NIST-on-a-Chip, NIST intends to bring NIST precise measurements to the application environment. Certain optical standards are currently fabricated at NIST, but the reproducibility and transportability of IPCs make them ideal for transitioning metrology technology to outside partners.

NIST also has interest as a user of Multi-Project Wafer runs. For integrated quantum photonics, NIST would combine silicon photonics with world-leading superconducting single photon detector technology. Mid-infrared supercontinuum generation would be enabled by integration of an optical frequency comb and dispersion engineered air-suspended silicon waveguides. For nanoscale cavity opto-mechanical sensors and signal transducers, optical readout could be integrated with MEMS sensors and radiation-pressure-mediated information transduction could be developed.

Since 2007, NIST has operated the Center for Nanoscale Science and Technology (CNST) in Gaithersburg, MD. As a national user facility, the CNST has a large user base across industry, academia, and government labs. Many photonics device developers already use CNST (NIST, academia, small companies). The CNST could provide front-end and back-end steps that are not likely to be offered (e.g., e-beam lithography, deposition of non-standard materials, wafer thinning, release for MEMS/NEMS). Furthermore, as the nation's metrology authority, NIST could foster the metrology required for the development of integrated photonics. There are two examples: inline metrology tools to test different parts of the wafer during different fabrication steps (e.g., evanescent coupling to test resonator/waveguide loss after etch steps) and design of optimal test structures for inclusion in fabrication runs that provide useful metrics (loss, doping, efficiency, etc.).

Department of Energy

For the Department of Energy, ARPA-E sees that Data Centers represent about 3% of the U.S. power grid. Within Data Centers, about half of the power draw is for data communications, which represents a

sufficiently large energy draw to warrant ARPA-E attention. One particular example is that of the Facebook Prineville data center in 2012, which consumed 153 million kilowatt hours of energy in 2012, equivalent to 13,000 homes [10]. The energy consumption of telecommunication and data communication links have seen growing attention in the past decade. [11] [12] [13]. Photonic nodes are expected to consume less power than electrical ones [11]. The top two recommendations from a recent study [14] are directed at integration: 1) Increase photonic and photonic-electronic integration to reduce power, size, and cost; increase performance; and enable parallelism, and 2) Optics on ASIC: Use optical integration on the ASIC. Most recently, a multi-chip macrochip design utilizing silicon photonic intra-node communications have been suggested for power-efficient petascale systems [15].

Dr. Haney, ARPA-E Program Director, held a workshop in the summer of 2015, yet he has concerns that silicon has many hurdles to overcome in order to solve this energy problem. Dr. Haney is interested in interconnects that range in distance from on-chip, to chip-to-chip, to board level, to rack-to-rack, and within the Data Center campus area. This range represents distances from a few millimeters to about 100 meters, or so. The underlying technology push is not yet focused on InP or Si, but is likely to include optical sources (lasers), waveguides, switches, VCSELs, grating couplers, waveguide couplers, and photodetection devices.

Department of Health and Human Services

The overlap of photonics and biology may start with the first organism sensitive to light and progress to photosynthesis, eye sight, and bioluminescence. Today's healthcare can benefit greatly from photonic techniques. Chemical-Biological agent detection and its well-defined relation to photonics is covered by DoD activities. The Department of Health and Human Services, on the other hand, generally seeks to enhance and protect health and well-being. This broad mission could involve photonics from countless perspectives.

Here, we focus on applications that could potentially realize large benefits from integrated photonics. Thus, the more familiar cellular/molecular microscopy and related 2-D imaging technologies are not addressed. Instead, recent emphasis has been on biosensors, quantitative chemical analysis, less invasive probing, and lab-on-chip systems. An example is the European Research Council commissioning of "Wideband Integrated Photonics for accessible Biomedical Diagnostics" [16] to advance the frontiers of biophotonics research in mid-IR materials systems, integrated photonic components for biochemical analysis and nanostructured photonic materials for light control.

The overall advantage of IPCs lies in their size, scalable manufacturing, and capability for parallel processing. One of the more prevalent examples of optical sensing devices are high-quality microring resonators that can be integrated with input-output optical waveguides, *Figure 8* [17]. The sensitivity enhancement of this device could be viewed as stemming from the light interacting with the foreign matter numerous times as it circulates around the resonator. Despite the slightly reduced performance of the integrated version of the resonator (due to IPC material constraints), there remains a strong attraction to IPC resonators due to the ease in sensor interrogation, fabrication scalability, and functionalization toward a multiplexed biomolecular detection capability.

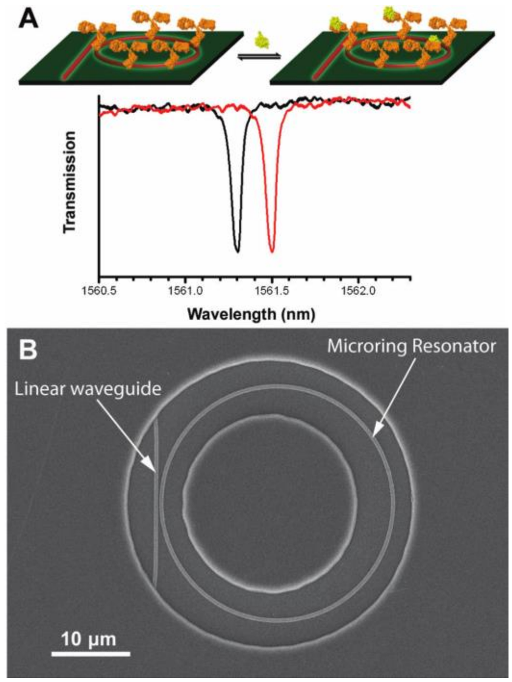

Figure 8 (A) Proteins (or other particulate) binding to microring resonator and associated shift in transmission null frequency. (B) Scanning Electron Microscope image of a silicon on insulator microring resonator **[17]**

An example of the ongoing research includes recent work from Universiti Teknologi, Malaysia where ring resonator is being targeted for Salmonella bacteria detection [18].

As for the Department role with respect to IPCs, it appears through various grants that the Department is interested in developing the technology. However, within the Center for Disease Control and Prevention or the National Institutes of Health, the authors have not identified any person or organization leading IPC advancement and utility for the Department of Health and Human Services.

Appendix E: List of Abbreviations

ADC	Analog-to-digital converter
A/G	Air/Ground
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
AWG	Arrayed waveguide grating
CAGR	Cumulative average growth rate
CB	Chemical and Biological
CMOS	Complementary metal-oxide-semiconductor
COTS	Commercial off-the-shelf
DoD	Department of Defense
DoE	Department of Energy
DARPA	Defense Advanced Research Projects Agency
DTRA	Defense Threat Reduction Agency
DWDM	Dense wavelength division multiplexing
DSB	Defense Science Board
EA	Electronic attack
EDA	Electronic design automation
EM	Electromagnetic
EP	Electronic protect
ES	Electronic support
EA MOD	Electro-absorption modulator
ELINT	Electronic Intelligence
FFRDC	Federally funded research and development center
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gb/s	Gigabits per second
InP	Indium Phosphide
IPC	Integrated photonic circuit
IP-IMI	Integrated photonic institute for manufacturing innovation
LED	Light-emitting diode
$LiNbO_3$	Lithium Niobate

MMI	Multi-mode interference
MIMIC	Microwave monolithic integrated circuits (1980s DARPA program)
MMIC	Monolithic microwave integrated circuit
mmW	Millimeter wave
MPW	Multi-project wafer
MZ MOD	Mach-Zehnder Modulator
PD	Photodetector
PIC	Photonic integrated circuit
PLC	Planar lightwave circuit
PNT	Positioning, Navigation, and Timing
QIS	Quantum Information Science
QKD	Quantum key distribution
RSA	Rivest-Shamir-Adleman cryptosystem
SOA	Semiconductor optical amplifier
SWAP-C	Size, weight, power, and cost
VOA	Variable optical attenuator